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METHOD AND SYSTEM FOR DETERMINING THE DENSITY AND DIMENSIONAL CHARACTERISTICS OF AN OBJECT AND APPLICATION TO CHECKING OF NUCLEAR FUEL PELLETS DURING MANUFACTURING

DESCRIPTION

Technical domain

This invention relates to the domain of non-destructive analysis techniques.

More specifically, the invention is applicable to a method and a system for automatic determination of the density of objects by straight line photon attenuation and their dimensional characteristics.

One of its applications is the inspection and monitoring of the correct operation of object manufacturing and machining units, for example such as nuclear fuel pellets such as UOX and/or MOX, and is used particularly to monitor reproducibility of manufacturing of said objects, related to their density.

It can also be used to determine axial and radial density gradients, thus acting as a very precise computed tomography (CT) scanner.

State of prior art

Non-destructive active nuclear methods for determination of the density have already been produced, particularly to determine the density of geological samples. In the reference document *Been, K., "Non-destructive Soil Bulk density Measurement by X-ray*

Attenuation" Geotechnical Testing Journal, GTJODJ, Vol. 4, No. 4, Dec. 1981, pp 169-176, the author proposes a samples density measurement by straight line photon attenuation using X-ray tubes, without attempting to precisely determine the dimension of the samples concerned. In reference documents *Tan, S.-A and Fwa T.-F., "Non-destructive Density Measurements of Cylindrical Specimens by Gamma-Ray Attenuation", Journal of Testing Evaluation, JTEVA, Vol. 19, No. 2, March 1991, pp. 155-160,* and *Tan, S.-A and Fwa, T.-F "Density Measurements of Cylindrical Specimens within a Mold by Gamma-Rays", Journal of Testing Evaluation, JTEVA, vol. 21, No. 4, July 1993, pp. 296-301,* the authors propose a measurement of the density of geological samples by straight line photon attenuation using gamma radiation. They have identified and demonstrated the influence of geometric parameters of samples on the precision of the density measurement, but they did not propose a solution to precisely determine said geometric parameters.

Note that although the documents mentioned above relate to the density of samples, the objective is actually to determine the mass per unit volume of said objects, and the term "density" is used instead of "mass per unit volume" to simplify the description.

<u>Presentation of the invention</u>

The purpose of this invention is to determine the density of objects belonging to a given set of objects, by determining the variation of the density of each of said objects with respect to the known density of at

least one of said objects used as a reference or a standard.

This determination of the density of said objects is made using a non-destructive nuclear technique, consisting of irradiation by gamma photons and using a gamma spectrometry apparatus to determine the intensity of the gamma photon beam.

Determination of the density of said objects requires prior determination of at least one significant dimension of the objects.

Unlike the methods described in prior art mentioned above, the invention takes account of the influence of geometric parameters by very precisely measuring at least one significant dimension of the objects for which the density is to be determined, and using this measured significant dimension to determine the density of the tested objects. Said significant dimension may be a width or a diameter and corresponds to the effective dimension through which the gamma photon beam passes.

The method for determination of the significant dimension of the object forms part of the method to determine the density of said object. It uses an infrared radiation apparatus for measuring the dimension.

Remember briefly that the physical principle for determination of the density of an object by photon attenuation consists of irradiating the object with a query beam composed of monochromatic photons with energy E. The intensity of the photon beam is attenuated more or less as a function of the density of

the object through which it passes, the thickness of the material through which it passes, and the elementary chemical composition of the object through which it passes. This intensity is given by the following equation:

$$I = I_O \exp(-\mu_m \rho X)$$

where:

- I is the attenuated intensity of the photon beam, in photons^{-1},

- I_O is the non-attenuated intensity of the photon beam with energy E, in photons^{-1},

- μ_m is the mass attenuation coefficient of the photon with energy E in the object, in $cm^2.g^{-1}$,

- ρ is the density of the object to be tested, in $g.cm^{-3}$,

- X is the thickness of the material through which the photon beam passes, or the significant dimension of the object, in cm.

The expression for the density of the object is deduced directly by:

$$\rho = \frac{Ln\left[\frac{I_O}{I}\right]}{\mu_m X}$$

Thus, if the intensities transmitted with and without insertion of the object to be tested (I and I_O respectively), the mass attenuation coefficient μ_m and the significant dimension x of the object actually

passed through are known, the density ρ of said object can be determined.

This invention proposes to determine the thickness of material x of the object through which the photon beam passes and the transmitted intensity I of the photon beam at energy level E, and to use these values to calculate the relative variation of the density ρ of this object with respect to the density of at least one reference standard object. One characteristic of the invention lies in the fact that these determinations of the material thickness (significant dimension of the object) and the intensity of the photon beam are made with a precision of about one micron.

The relative variation of the density ρ of the object to be tested is obtained using the following expression:

$$\frac{\Delta\rho}{\rho} = \frac{\rho - \rho_e}{\rho} = \frac{x_e}{x}\left[1 = \frac{L_n \dfrac{I}{I_e}}{\mu_m \rho_e x_e}\right]$$

where ρ_e is the known density of the object used as a density standard, and x_e is the significant dimension passed through in the object with standard density.

The mass attenuation coefficient μ_m that depends on the chemical composition of the object, is determined from one or several certified and perfectly known standard objects, with the same chemical composition as the object to be tested. It is determined during one step that will be described in

the following, for calibration of the apparatus to determine the intensity of the photon beam, attenuated by passing through the standard object.

When the object to be tested has a circular section, the significant dimension passed through corresponds to its diameter. When the object to be tested is parallelepiped in shape, the significant dimension passed through is a width of the object.

In the rest of the description, the following notations will be used when it is required to distinguish an object i among the set of objects 100 and/or a standard object e among the set of objects 100:

- the index emas is representative of magnitudes relative to an object with standard density, for example its significant dimension x_{emas},

- the index edim is representative of magnitudes relative to an object with standard dimension, for example its significant dimension x_{edim}.

According to a first aspect of the invention, the system for automatic determination of the density of an object belonging to a set of objects comprises:

- an apparatus to determine a significant dimension of said object,

- an apparatus to determine the intensity of a photon beam attenuated by passing through said object,

- an acquisition, processing and analysis apparatus,

- means of transporting the object to the apparatus for determining its significant dimension and

towards the apparatus for determining the attenuated intensity of the photon beam,

- first means of adjusting the position of the object relative to the apparatus for determining the significant dimension,

- second means of adjusting the position of the object relative to the apparatus for determining the attenuated photon intensity,

said first and second adjustment means being capable of moving the object with a precision of the order of one micron with respect to a support plate on which the elements making up the system are installed,

and the position of the object relative to the apparatus for determining the attenuated intensity being adjusted as a function of the significant dimension of said object.

Preferably, the apparatus for determining a significant dimension of the object is a measurement apparatus using infrared radiation.

Preferably, the apparatus to determine the intensity of a photon beam attenuated by the crossing through the object is a gamma spectrometry determination apparatus, that comprises:

- an assembly composed of a source and a collimator,

- an assembly composed of a detector and a collimator,

- a gamma photon acquisition and counting system.

The invention uses transport means and means of adjusting the position of each tested object with respect to the apparatus for determining the

significant dimension of the object and/or with respect to the apparatus for determining the attenuated intensity, said position adjustment means being capable of providing a precision of the order of one micron.

According to a second aspect, the invention relates to a process for using the system for automatic determination of the density of an object (100) belonging to a set of objects, and includes the following calibration steps:

- a step 1 to calibrate the position of two infrared assemblies in the apparatus to determine the significant dimension of objects,

- a step 2 to calibrate the position of an irradiation support of the gamma spectrometry apparatus used to determine the intensity of the photon beam attenuated by passing through objects,

- a step 3 to calibrate the measurement of a source-detector assembly of the gamma spectrometry apparatus used to determine the intensity of the photon beam attenuated by passing through objects,

and it includes steps to actually determine the significant dimension of objects, which are done on each object in said set of objects.

According to the invention, the actual determination steps include:

- a step 4 to determine the significant dimension of the object to be tested,

- a step 5 to transport the object to an irradiation support,

- a step 6 to adjust the position of the object by adjusting the position of the irradiation support with respect to a source and an associated detector,

- a step 7 to determine the attenuated intensity of the photon beam transmitted through the object,

- a step 8 for acquisition, processing and analysis of the spectrum obtained,

- a step 9 for determination of the relative variation $\frac{\Delta\rho}{\rho}$ of the density of the object with respect to the density of one or several object(s) with standard density,

- a transport step 10 to return the object to its position on the turntable.

The methods and devices according to the invention have the advantage that they are fast, precise, automatic or can be automated, and are easy to use.

One advantage of the invention lies in the fact that it associates straight line photon attenuation with micrometric metrology so as to overcome uncertainties related to poor knowledge of the thicknesses of objects passed through, and that directly affect the precision with which the density is determined.

In particular, the position of each object relative to the apparatus used to determine the photon intensity attenuated by the crossing through said object is adjusted as a function of a significant dimension of the object, and that had previously been determined by the apparatus used to determine the significant dimension.

Brief description of the figures

The invention will be better understood after reading the detailed description of a preferred embodiment given below as a non-limitative example that is illustrated by the appended figures, wherein:

- Figure 1 shows a diagrammatic top view of the general system for determination of the significant dimension and for determination of the density of objects,

- Figure 2 shows a diagrammatic perspective view of the general system for determination of the significant dimension and for determination of the density of objects,

- Figures 3, 4 and 5 illustrate a diagrammatic top view of the device for determination of a significant dimension of objects by means of infrared radiation, and three phases in the method to determine this significant dimension,

- Figure 6 shows a perspective and sectional view of the collimator in the photon irradiation source,

- Figure 7 shows a perspective and sectional view of the collimator in the gamma photon detector,

- Figure 8 is a diagrammatic view showing the acquisition and counting system,

- Figures 9A and 9B show all steps in the method for determination of the density of objects; Figure 9A illustrates preliminary calibration steps and Figure 9B illustrates the actual determination steps;

- Figure 10 illustrates the first step in the method that is a step to calibrate the position of the apparatus to determine the significant dimension;

- Figure 11 illustrates the second step of the method that is a step to calibrate the position of the apparatus to determine the attenuated photon intensity;

- Figure 12 illustrates the third step of the method that is a step to calibrate the measurement of the apparatus to determine the attenuated photon intensity;

- Figure 13 illustrates the fourth step of the method that is a step to determine the significant dimension of an object;

- Figure 14 illustrates the ninth step of the method that is a step to determine the relative variation of the density of the object with respect to the relative variation of one or several standard objects;

- Figure 15 is a graph showing the relative variation of the density of the objects in a given set of objects relative to the density of one of the standard or reference objects, and compares this relative variation of density obtained by the invention with the relative variation of the theoretical density provided by the objects manufacturer.

<u>Detailed presentation of one particular embodiment</u>

Figures 1 and 2 illustrate a top view and a perspective view respectively of a preferred embodiment of the general system for determination of the density of each object 100 in a set of objects by photon

attenuation, by determining the relative variation of this density with respect to the density of at least one of said objects used as a standard density or reference, this density determination making use of the preliminary determination of a significant dimension x of said object 100, and the intensity I of the photon beam that irradiates and passes through said object 100.

The system includes the following components:

- an apparatus 2 for determination of the significant dimension of the object 100,

- an apparatus 30 for determination of the intensity of the photon beam attenuated by passing through the object 100,

- an acquisition, processing and analysis apparatus 200,

- transport means 70, 72, 80, 82, 84, 86, 88 and position adjustment means 74, 76, 78, 90, 92, 94, 96, 98 of the object 100 with respect to the dimension determination apparatus 2 with respect to the intensity determination apparatus 30, respectively.

The acquisition, processing and analysis apparatus 200 is shown diagrammatically as a whole in Figure 1. In particular, it includes a PC type computer 170 on which a dedicated software is installed that runs series of instructions and calculation algorithms used in the automatic method for determination of the density of objects 100 according to the invention.

With reference to Figures 3, 4 and 5, the infrared radiation apparatus 2 used for determination of a significant dimension x of the object 100 includes:

- a first infrared assembly 4, 6 composed of a first infrared emitter 4 and a first infrared receiver 6,

- a second infrared assembly 8, 10 composed of a second infrared emitter 8 and a second infrared receiver 10.

The two infrared assemblies 4, 6, and 8, 10 are arranged such that the corresponding axes 12, 14 of the infrared radiation beams that they generate are parallel to each other and are separated by a distance d. This distance d fixed by the manufacturer is chosen so as to be of the same order of magnitude as the significant dimension x of objects 100 to be tested. It is adjustable. The infrared beams are oriented in the same direction in the example illustrated, but a different configuration could be envisaged.

The apparatus 2 for determination of the significant dimension x of the object 100 by infrared radiation also includes a third assembly composed of a photoelectric emitter 16 and a photoelectric receiver 18, arranged on the input side of the first infrared assembly 4, 6 with respect to the second infrared assembly 8, 10, the photoelectric beam that it generates having an axis 19. In the example shown, the axis 19 of the photoelectric beam is parallel to the axes 12, 14 of the infrared beams, and is located in the same plane as them. A different configuration could be envisaged.

The apparatus 2 for determination of the significant dimension x of the object 100 by infrared radiation is associated with transport means and/or

means of adjusting the position of the object 100 with respect to the three transceiver assemblies 4, 6, 8, 10, 16, 18 that will be described in the following.

During operation, the apparatus 2 for determination of the significant dimension of the object 100 is located in a situation in which the three transceiver assemblies 4, 6, 8, 10, 16, 18 are fixed, and the object 100 is displaced so as to successively intercept the photoelectric beam, then the first infrared beam, then the second infrared beam.

The apparatus 2 is calibrated so as to create a distance d between the axes 12 and 14 of the two infrared radiation beams that are substantially the same as the significant dimension x_{edim} of one or several objects with standard dimension edim. This calibration will be described later. It then follows that during determination of the significant dimension of object 100 (non standard), the object moves relative to the three transceiver assemblies 4, 6, 8, 10, 16, 18 and passes through at least one position in which it still intercepts half of the first infrared beam (Figure 5, reference 22) and does not yet intercept the entire second infrared beam, leaving a fraction of the second beam (Figure 5, reference 24) that is not intercepted by the object 100, and that reaches the second receiver 10.

The significant dimension x of the object 100 is deduced from the infrared response RI corresponding to this non intercepted beam fraction. This dimension is obtained by a relation of the following type:

$$x = A_4.(RI^4) + A_3.(RI^3) + A_2.(RI^2) + A_1.(RI^1) + A_0,$$

where A_4, A_3, A_2, A_1, A_0 are coefficients obtained using at least four objects with standard dimension edim, and applying the same relation in which the known significant dimension x_{edim} and the measured infrared response RI_{edim} of each of said objects with standard dimension edim are injected, once for each object with standard dimension.

As shown in Figure 4, the function of the third assembly 16, 18 is to automatically trigger prior adjustment of the intensity of the two infrared beams 22, 24, when the object 100 intercepts the photoelectric beam generated by this third assembly 16, 18, during the relative displacement along the direction 20. The purpose of this operation is to eliminate the influence of environmental disturbances such as optical lenses getting dirty. It must occur not later than 30 seconds before the measurement operation itself on the object 100.

The precision with which the significant dimension x of the object 100 is determined depends on the precision of the relative displacement of the object 100 with respect to the three transceiver assemblies 4, 6, 8, 10, 16, 18 and therefore on the performances and calibration of the transport and/or position adjustment means, aspects that will be described in more detail later.

According to the invention, the intensity I of the photon beam is determined using a gamma spectrometry apparatus 30 to determine the intensity of the photon

beam that irradiates and passes through the objects 100, as shown in Figures 1, 2 and 8. This includes:

- an assembly formed from a photon irradiation source and a collimator 32, of a type known in itself,
- an assembly formed from a detector and a collimator 40, of a type known in itself,
- an acquisition and counting system 48, of a type known in itself.

The photon irradiation source will be called the "source" in the following, to simplify the description.

The different components of the determination apparatus 30 are subjected to some constraints related to the required performance for the general system, and the environment in which the system will operate. These constraints, that relate particularly to the source intensity, the source type and the performances of the acquisition and counting system, are as follows:

- the intensity of the source must be such that the statistical dispersion of the measurement results is significantly less than the count variation due to a difference in the density of the object to be tested with respect to the density of the reference standard object,
- the source energy must enable very good contrast following a minor variation of the density of the object to be tested,
- the radioactive half-life of the source must not be too short so that it is restrictive in an industrial environment,
- finally, the intensity and the energy of the source must be compatible with processing capabilities

of the electronic acquisition and counting system (dead time, stacking, saturation, etc.).

In the preferred embodiment, the source is made of ^{133}Ba with an activity of at least 10 mCi. To avoid the effects of dead time and/or saturation, it is preferable to use a source with an activity not exceeding 150 mCi. The measurement duration is inversely proportional to the activity of the source.

Figure 6 illustrates an example embodiment of the collimator 32 of the source-collimator assembly, compatible with these different constraints. It includes a protection formwork 34 to protect persons working close to the source that delimits a cavity 36 in which the source is housed. The gamma photon beam is guided by a collimation slit 38.

According to the example embodiment illustrated, the collimator 32 of the source is made of lead and its outside dimensions are 60 mm in height, 60 mm in length and 60 mm in width. The source is a ^{133}Ba source with an activity of 10 mCi, housed in a cavity 36 with a diameter of 6.1 mm and a height of 9.5 mm. The collimation slit 38 is 30 mm long, 6 mm wide and 4 mm high.

Figure 7 shows an example embodiment of the collimator 40 in the detector-collimator assembly. It includes a protection formwork 42 so that the gamma rays output from the source and emitted outside the collimation slit 38 are not detected by the detector 49, a collimation slit 44 and a cavity 46 to house the detector 49 delimited by the protection formwork 42.

In the example embodiment shown, the collimator 40 of the detector 49 is made of lead and its outside dimensions are 140 mm in diameter and 120 mm in length, and its inside dimensions are 80 mm in diameter and 200 mm long. The collimation slit is 4 mm high, 6 mm wide and 30 mm long.

The lead in the protection formwork 42 may be replaced by tungsten that attenuates gamma rays more than lead, which has the advantage that it reduces the thickness of the protection formwork 42, but the disadvantage of tungsten is that its price is higher than the price of lead.

In the following and to simplify the description, the source-collimator assembly will simply be called the "source" and will be marked as reference 32, and the detector-collimator assembly will simply be called the "detector" and will be marked as reference 40.

The source-detector distance is chosen appropriately.

According to the preferred embodiment, the acquisition and counting system 48 shown in Figure 8 includes:

- a detector 49 in the form of a high purity germanium Ge diode [HP] with a preamplifier,
- a digital signal processor (DSP) 50,
- a high voltage module 54,
- an acquisition and interface network module (AIM) 56,
- a PC type data acquisition computer 170 (Figure 1).

Optionally, the acquisition and counting system includes a cryostat 60 composed of a liquid nitrogen tank that keeps the cold finger of the Ge diode [HP] at a constant temperature, which has the advantage of minimising the Doppler effect and giving very good signal resolution, the measurements not being disturbed by heating of the detector 49.

The preamplifier is preferably incorporated into the Ge diode [HP], which has the advantage of minimising the capacitance effect due to the electrical cable and reduces electronic background noise. It also filters and shapes the signal.

The signal is then digitised using the signal processing module 50 and is then put into memory.

The set of information obtained makes up the gamma spectrum, in other words the histogram sorting the number of pulses into different channels as a function of their energy.

Data are transferred (arrow 62) between the signal processing module 50 and the computer 170 of the acquisition, processing and analysis apparatus 200, through the acquisition and interface network module 56, a transceiver 63, a network card 59. In the example illustrated, the acquisition, processing and analysis apparatus 200 and the acquisition and counting system 48 use the same computer 170, but a configuration with two separate computers could be envisaged.

This acquisition and counting system 48 is particularly suitable for high counting rates.

Furthermore, another constraint for use of the gamma spectrometry apparatus 30 for determination of

the intensity of the photon beam that irradiates the objects 100 relates to the count time of the acquisition and counting system 48, that must respect manufacturing rates of objects 100 to be tested.

According to the invention, the count time can be a system input data, or the result of a calculation output by the following theoretical relation:

$$t = \frac{\alpha^2}{A(t).\frac{S}{4\pi D^2}.\varepsilon.\frac{\sum}{P}.R_0.\left(R_O^{\beta_{SEC}} - 1\right)^2}$$

with an approximation by which the solid angle is equal to $4\pi D^2$.

where:

A(t) is the activity of the source in Bq,

D is the distance between the source and a collimation window, in mm,

S is the surface area of the detector collimation window, in mm^2,

α is the width of the confidence interval for the case in which counting follows a Poisson's distribution,

ε is the total absorption efficiency of the photon detector,

I is the intensity of the photon beam at energy E, attenuated by crossing through the object, in $\gamma.s^{-1}$,

I_0 is the non-attenuated intensity of the photon beam at energy E, in $\gamma.s^{-1}$,

$R_O = \frac{I}{I_o}$ is the transmission coefficient of the object through which monochromatic photons output by the source pass,

Σ is the total number of hits recorded in the measured spectrum, in hits,

P is the total number of hits contained in the energy peak E,

$\beta_{SEC} = \frac{\beta}{IO}$ is a value of β assigned by a safety factor equal to 10,

where $\beta = \frac{\Delta\rho}{\rho}$,

and where ρ is the density of the object.

The precision to which the intensity I attenuated by passing through the object 100 is determined depends particularly on the position of said object 100 with respect to the source 32. Therefore, it depends on performances and calibration of the position adjustment means. These aspects will be described in more detail later.

The different transport means 70, 72, 80, 82, 84, 86, 88 and position adjustment means 74, 76, 78, 90, 92, 94, 96, 98 are shown in Figures 1 and 2 showing the system as a whole. Their purpose is to transport the object 100 to each apparatus 2, 30 used to determine or adjust the relative position of the object 100 with respect to the elements making up each determination apparatus 2, 30.

A support plate 150 supports components of the general system, namely the apparatus 2 used to

determine the significant dimension, the apparatus 30 used to determine the attenuated intensity of the beam, the transport means, the first adjustment means and the second adjustment means. The displacement directions are shown diagrammatically by coordinate system 152 in Figure 2. Displacements take place in the horizontal plane (X, Y) of the support plate 150, or along the vertical direction Z perpendicular to the horizontal plane (X, Y) of the support plate 150.

The transport means 70, 72 are designed to transport the object 100 into a first position in which the apparatus 2 determines the significant dimension of said object 100. They include a horizontal turntable 70 activated by a stepping motor 72, both installed on the support plate 150. In the example shown, the turntable 70 includes twelve object locations.

The first adjustment means 74, 76, 78 are designed to adjust the position of the object 100 with respect to the two infrared assemblies 4, 6 and 8, 10 that are used to measure the significant dimension x of the object 100.

The adjustment means 74 is a slide oriented along the X direction, along which the base 26 of the infrared radiation apparatus 2 used to determine the dimension, and the turntable 70 are located.

The two infrared assemblies 4, 6 and 8, 10 are installed on the base 26 such that the axes 12, 14 of the infrared beams are parallel to the direction X. For a given set of objects for which the dimensions are substantially all of the same order of magnitude, the relative positions of the base 26 and the turntable 70

along this direction X are preferably fixed once and for all at the beginning of the series of measurements for the given set of objects.

The adjustment means 76 is an actuator, the function of which is to bring the first infrared assembly 4, 6 closer to or further from the second infrared assembly 8, 10 along the Y direction. This displacement of the first infrared assembly 4, 6 along the Y direction provides a means of positioning the object 100 with a precision of about one micron with respect to the two infrared radiation beams to determine its significant dimension X (diameter or thickness).

The adjustment means 78 is an actuator, the function of which is to move the base 26 along the Z direction. The amplitude of this displacement is relatively small, so as to prevent the base 26 from coming out of the slide 74. Displacement of the base along the Z direction provides a means of obtaining the dimension of the object 100 used to determine its significant dimension x, with a precision of about one micron.

The transport means 70, 72, 80, 82, 84, 86, 88 also perform the function of displacing the object 100 from its first position in which the apparatus 2 determines the significant dimension x towards its second position in which the apparatus 30 determines the attenuated intensity I of the photon beam. They include the turntable 70 driven by its stepping motor 72. Several objects 100 are located on a circle on the turntable 70, rotation of said plate 70 performs two

simultaneous actions consisting firstly of transporting an object 100 to its first measurement position and secondly moving the previous object 100 from its first measurement position to bring it to an intermediate position after it had performed an angular displacement of an angle A. In the example illustrated in Figures 1 and 2, this angle A is 90°. The transport means also include a handling arm 80 that grips the object 100 installed on the turntable 70 in its intermediate position and transports it on an irradiation support 90 located between the collimator 32 of the source and the collimator 40 of the detector. In the example illustrated in Figure 2, the handling arm 80 comprises a gripping clamp 82 articulated on an intermediate segment 84, itself articulated on an actuator 86 capable of moving in translation along the X direction of the support plate 150, along guide rails 88. Tightening/loosening movements of the clamp 82 and pivoting movement of it about the segment 84, and pivoting movements of the segment 84 with respect to the actuator 86 are controlled by actuators (not shown).

The function of the second adjustment means 90, 92, 94, 96, 98 is to adjust the position of the object 100 with respect to the source 32 and the detector 40 of the gamma spectrometry apparatus 30 to determine the intensity of the beam that will pass through said object 100. They include the irradiation support 90 on which the object 100 is installed. This irradiation support 90 has a top face 92 with a V-shaped cross-section, or any other equivalent means such that the

object 100 is automatically installed in a stable equilibrium position on said irradiation support 90, and particularly that it cannot move with respect to the irradiation support 90 along the X direction of the support plate 150. The irradiation support 90 is positioned along the X direction of the support plate 150 by means of a slide 94 that is preferably coincident with the slide 74. For a given set of objects 100, this positioning is done once and for all at the beginning of the series of measurements corresponding to a given set of objects. The irradiation support 90 may be moved along the Y direction of the support plate 150 by means of an actuator 96 and along the Z direction perpendicular to the support plate 150 by means of an actuator 98. The position adjustments made using the actuators 96 and 98 substantially centre the object (along the Z direction) between the slits of the corresponding collimators of the source 32 and the detector 40.

Furthermore, it is necessary to position the object along the Y direction with a precision of about one micron such that the intensity I of the photon beam is measured at exactly the dimension of the object at which its significant dimension x was determined. This positioning is done by bringing the object until it stops on the upper face 92 of the irradiation support 90. For example, it may be brought into contact with this stop by a blowing operation using a blowing device (not shown), that forces compressed air onto the object, along the Y direction, so as to force it into contact with a stop 93 of the irradiation support 90.

Figure 1 shows connections through appropriate connection means 180 between firstly the different actuators 76, 78, 86, 96, 98 displacing parts free to move in translation and the stepping motor 72 that rotates the turntable 70, and secondly control and steering units 160. These units 160 control the mechanics and automation of the system, and are connected to the system unit 172 of the computer 170 of the acquisition, processing and analysis apparatus 200, by other appropriate connection means 190.

We will now describe the method for determining the density ρ of each object in a given set of objects 100, by comparison with the density ρ_{emas} of one or several objects chosen as standard or reference density, and forming part of the same set of objects 100.

The method is used with algorithms translating series of instructions that automatically perform the different steps in the method.

The method according to the invention includes preliminary calibration steps that are done once and for all before beginning a series of measurements on a given set of objects, and actual determination steps that are done on each object 100 in said set of objects. All steps in the method are shown schematically in Figures 9A and 9B.

The calibration steps follow a predetermined chronology and relate to the following components of the system:

- step 1: calibration of the position of the two infrared assemblies 4, 6 and 8, 10 of the apparatus 2

for determination of the significant dimension of objects 100,

- step 2: calibration of the position of the irradiation support 90 of the gamma spectrometry apparatus 30 for determining the intensity of the photon beam attenuated by crossing through objects 100,

- step 3: calibration of the measurement of the source-detector assembly 32, 40 of the apparatus 30.

The position calibration step 1 of the two infrared assemblies 4, 6 and 8, 10 is shown in Figure 10.

This calibration step 1 consists of adjusting the position along the Y direction of the first infrared assembly 4, 6 with respect to the second infrared assembly 8, 10, so as to fix the distance d between the infrared beams emitted by the two emitters 4, 8 respectively, as a function of the precisely known significant dimension x_{edim} of one or several objects with standard dimension edim. In practice, the distance d is determined by progressively moving the first infrared assembly 4, 6 away from the second infrared assembly 8, 10 along the Y direction, the second infrared assembly remaining fixed at a position Y_{FIX}, and measuring the infrared response of the object for each position of the first infrared assembly 4, 6.

The position calibration step 1 of the two infrared assemblies 4, 6 and 8, 10 includes firstly operator input of a set of input parameters using an interactive module. These parameters include:

- configuration of components that have a micrometric displacement; actuators 76, 78 that manage their dynamics: position, velocity, acceleration,

- configuration of the turntable 70, in other words the nature of the objects that occupy the different locations on the turntable 70; arbitrary object 100, or standard dimension object edim, or standard density object emas, or free location,

- the position occupied by standard dimension objects edim on the turntable 70, this location being a number varying from 1 to 12 for the example shown,

- the position $Z_{measure}$ along the Z direction of the base 26 of the apparatus 2, that corresponds to a dimension Z_{edim} on the object edim with respect to the base of the object,

- the positions Y(1) and Y(N) limiting the displacement interval of the first infrared assembly 4, 6 along the Y direction,

- the step INT expressed in µm of the displacement of the first infrared assembly 4, 6 along the Y direction ($\frac{Y_{DEP} - Y_{ARR}}{INT}$ must be an integer number).

The step 1 to calibrate the position of the two infrared assemblies 4, 6 and 8, 10 then includes the following automated operations:

a) displacement of the base 26 along the Z direction as far as the $Z_{measure}$ position by actuation of the actuator 78,

b) angular displacement of the turntable 70 so as to transport the standard dimension object edim as far

as its initial measurement position with respect to the apparatus 2,

c) displacement of the first infrared assembly 4, 6 along the Y direction as far as its start position Y(1) by actuation of the actuator 76,

d) progressive displacement of the first infrared assembly 4, 6 along the Y direction in successive increments of INT, moving it away from the second infrared assembly 8, 10 fixed at a position Y_{FIX} between the Y(1) and Y(N) positions, and simultaneously determination of the infrared response RI(n) of the object edim corresponding to each position Y(n) as follows:

d-1) angular displacement of the turntable 70 so as to transport the standard dimension object edim to its final measurement position,

d-2) measure the infrared response RI(n) of said standard dimension object edim,

d-3) angular displacement of the turntable 70 so as to bring the standard dimension object edim to its initial measurement position,

e) calculate the optimum infrared response $RI_{OPT} = \frac{RI_{MAX} - RI_{MIN}}{2}$

where: RI_{MIN} is the value of the minimum saturation of the infrared response; at the beginning of the calibration, separation between the two infrared assemblies 4, 6 and 8, 10 is very much less than the significant dimension x_{edim} of the standard dimension object edim; consequently, when 50% of the

first infrared beam is intercepted by the object edim, 100% of the second infrared beam is intercepted by this object edim; the first infrared responses then have an identical so-called "saturated" value RI_{MIN},

and: RI_{MAX} is the value of the maximum saturation of the infrared response; at the end of the calibration, separation between the two infrared assemblies 4, 6 and 8, 10 is very much greater than the significant dimension x_{edim} of the standard dimension object edim; consequently, when 50% of the first infrared beam is intercepted by the object edim, 0% of the second infrared beam is intercepted by this object edim; the last infrared responses then have an identical so-called "saturated" value RI_{MAX},

f) calculate the optimum position Y_{OPT} of the first infrared assembly 4, 6 with respect to the second infrared assembly 8, 10; the optimum infrared response RI_{OPT} is between two previously calculated successive values RI(j) and RI(k) of the infrared response, that correspond to the two positions Y(j) and Y(k) of the first infrared assembly 4, 6 respectively; the optimum position YOPT is deduced from these values as follows:

If $\frac{RI_{OPT} - RI(j)}{RI_{OPT} - RI(k)} < 1$, then $Y_{OPT} = Y(j)$

If $\frac{RI_{OPT} - RI(j)}{RI_{OPT} - RI(k)} > 1$, then $Y_{OPT} = Y(k)$

Operations a) to f) above may be repeated using as many standard dimension objects edim as necessary.

At the end of the step 1 to calibrate the position of the two infrared assemblies 4, 6 and 8, 10, a first calibration file is created that in particular comprises the optimum distance d of the two infrared assemblies 4, 6 and 8, 10 corresponding substantially to the significant dimension of objects d = $\|Y_{FIX} - Y_{OPT}\|$.

The position calibration step 2 of the irradiation support 90 of the gamma spectrometry apparatus 30 for determining the intensity of the photon beam attenuated by passing through the objects 100 is illustrated schematically in Figure 11.

This calibration step 2 consists of adjusting the position along the Z direction of the irradiation support 90 with respect to the source 32 and the associated detector 40, so as to fix the position Z_{OPT} along the Z direction of the top face 92 of the irradiation support 90 on which the objects 100 passed through the photon beam are positioned, as a function of the precisely known density ρ of one or several standard density objects emas. In practice, the position Z_{OPT} is determined by gradually moving the irradiation support 90 along the Z direction and irradiating the standard density object emas installed on the irradiation support 90 several times for each position of this irradiation support. It is determined by calculating a minimum of an order 4 polynomial regression. It includes a step to determine the significant dimension x_{emas} of each standard density object emas.

The step 2 to calibrate the position of the irradiation support 90 of the apparatus 30 comprises firstly a step in which an operator inputs a set of input parameters using an interactive module. These parameters include:

- configuration of components that have a micrometric displacement: actuators 96, 98 used to manage their dynamics: position, velocity, acceleration,

- configuration of the turntable 70, in other words the nature of the objects that occupy the different positions on the turntable 70; arbitrary object 100, or standard dimension object edim, or standard density object emas, or free location,

- the location occupied by the standard density objects emas on the turntable 70, this position being a number varying from 1 to 12 for the example shown,

- the measurement duration or count time,

- the positions Z(1) and Z (N) limiting the displacement interval of the irradiation support 90 along the Z direction,

- the number M of the measurements of the photon intensity attenuated by passing through the object, for each position Z(i) occupied by the irradiation support, for i = 1, …, N.

The step 2 to calibrate the position of the irradiation support 90 of the apparatus 30 then includes the following automated operations:

a) determination of the significant dimension x_{emas} of the standard density object, in accordance with step 4 that will be described below,

b) angular displacement of the turntable 70 by an angle A, in order to transport the standard density object emas into an intermediate position in which it will be gripped by the gripping arm 80,

c) position of the object emas on the irradiation support 90, that comprises the following sub-operations:

c-1) displacement of the irradiation support 90 downwards and along the Z direction by actuation of the actuator 98,

c-2) displacement of the handling arm 80 from its waiting position to become vertically in line with the intermediate position of the object emas, by actuation of the actuator 86,

c-3) gripping the object emas by the handling arm 80, and then transport of the object until it is vertically in line with the top face 92 of the irradiation support 90, by actuation of the actuator 86,

c-4) displacement of the irradiation support 90 as far as the position Z(1), upwards and along the Z direction, by actuation of the actuator 98,

c-5) put the object emas down on the top face 92 of the irradiation support 90 using the handling arm 80, by actuation of the actuator 86,

c-6) displacement and return of the handling arm 80 as far as its waiting position, by actuation of the actuator 86,

c-7) force the object emas into contact with a stop on the top face 92 along the Y direction, for

example by a blowing operation that takes place as follows:

- displacement of the irradiation support 90 downwards along the Z direction as far as a so-called blowing position in which the object is facing a blowing device provided in the system,

- send compressed air from the blowing device onto the object emas along the Y direction so as to force it into contact with a stop 93 on the irradiation support 90,

d) actual adjustment of the position of the irradiation support 90 with respect to the source 32 and the associated detector 40 that includes the following sub-operations:

d-1) progressive displacement of the irradiation support 90 along the Z direction between the predetermined position Z(1) and the predetermined position Z(N),

d-2) for each position Z(i), i = 1, …, N, irradiation of the standard density object emas by the photon beam a number M of times, which leads to a set of values of attenuated intensity I(i, J), where i = 1, …, N represents the number of successive positions Z(i) occupied by the irradiation support 90 and j = 1, …, M represents the number of irradiations made at each position Z(i),

d-3) calculate the optimum position Z_{OPT} of the irradiation support 90 starting from an order 4 polynomial regression of positions Z(i) with respect to the attenuated intensities I(i, j), this order 4 polynomial regression being predetermined and

integrated as a data item of the acquisition, processing and analysis apparatus 200,

e) return transport of the object with standard density emas on the turntable 70 using a sequence of operations the same as the sub-operations c-1) to c-6) described above but in the reverse order.

After completion of step 2 to calibrate the position of the irradiation support 90 of the gamma spectrometry apparatus 30 for determining the intensity of the photon beam attenuated by passing through the objects 100, a second calibration file is created that in particular comprises the optimum position Z_{OPT} of the irradiation support 90 along the Z direction.

Step 3 to calibrate the measurement of the gamma spectrometry determination apparatus 30 includes the following automated operations:

a) measurement of the photon intensity I_{emas} attenuated by passing through a standard density object emas used as a reference,

b) calculate the attenuation mass coefficient μ_m of the standard density object, and then of all objects in the set of objects using the following relation:

$$\rho_{emas} = \frac{1}{\mu_m xemas} . L_n \frac{I_{emas}}{I_O}$$

At the end of step 3 to calibrate the measurement of the gamma spectrometry apparatus 30 to determine the intensity of the photon beam attenuated by passing through objects 100, a third calibration file is created that in particular includes the photon

intensity I_{emas} attenuated by passing through the standard density object emas.

The actual determination steps also follow a predetermined chronology and concern the following operations:

- step 4: determine the significant dimension x of the object 100 to be tested,

- step 5: transport the object 100 towards the irradiation support 90,

- step 6: adjust the position of the object 100 by adjusting the position of the irradiation support 90 with respect to the source 32 and the associated detector 40,

- step 7: determine the attenuated intensity I of the photon beam transmitted through the object 100,

- step 8: acquisition, processing and analysis of the spectrum obtained,

- step 9: determination of the relative variation $\frac{\Delta\rho}{\rho}$ of the density of the object 100, relative to the density of one or several standard density objects emas,

- step 10: return transport of the object 100 as far as its location on the turntable 70.

Step 4 to determine the significant dimension x of the object 100 to be tested is illustrated schematically in Figure 13. It consists firstly of the operator inputting a set of input parameters using an interactive module. These parameters include:

- configuration of components that have a micrometric displacement: actuators 76, 78 used to manage their dynamics: position, velocity acceleration,

- configuration of the turntable 70, in other words the nature of objects that occupy the different locations on the turntable 70; arbitrary object 100, or standard dimension object edim, or standard density object emas, or free location,

- the location occupied by the object 100 on the turntable 70, this location being a number varying from 1 to 12 for the example shown,

- the position $Z_{measure}$ along the Z direction of the base 26 of the apparatus 2, that corresponds to a dimension z on the object 100 with respect to the base of the object,

- the number P of infrared measurements for each standard dimension object edim(n), n = 1, …, N, where N is the number of standard dimension objects,

- the number Q of infrared measurements for the object 100.

Step 4 to determine the significant dimension x of the object 100 to be tested also uses data contained in the first calibration file output from step 1.

The step 4 to determine the significant dimension x of the object 100 to be tested then includes the following automated operations:

a) displacement of the base 26 along the Z direction as far as the position $Z_{measure}$, by actuation of the actuator 78,

b) displacement of the first infrared assembly 4, 6 along the Y direction, by actuation of the actuator 76, as far as the position $Y_{measure}$ defined by:

$$Y_{measure} = Y_{OPT} + (X_{edim} - X_{edimAVE})$$

where:

Y_{OPT} is the optimum position obtained in calibration step 1, this value being contained in the first calibration file,

X_{edim} is the dimension of the standard dimension object edim used during the calibration step 1, this value being contained in the first calibration file,

$X_{edimAVE}$ is the significant average dimension of all standard dimension objects edim, this value being given by the manufacturer,

c) measurement of the infrared response RI(p), repeated P times, p = 1, …, P of N standard dimension objects edim(n), n = 1, …, N, which leads to a set of values RI(n, p),

d) calculation of the significant dimension x of the object 100 as follows:

d-1) calculate the average $RI_{edimAVE} = \frac{\sum RI(n,p)}{P}$ of the infrared responses of each standard dimension object edim(n) for which the significant dimension $x_{edim}(n)$ is known, and use of an order 4 polynomial regression of the significant dimensions $x_{edim}(n)$ to calculate the coefficients A_0, A_1, A_2, A_3, A_4 of a relation of the following type:

$$x_{edim}(n) = A_4 \cdot (RI_{edimAVE}\ (N))^4 + A_3 \cdot (RI_{edimAVE}\ (n))^3 + A_2 \cdot (RI_{edimAVE}\ (n))^2 + A_1 \cdot (RI_{edimAVE}\ (n))^1 + A_0,$$

d-2) measurement of the infrared response RI(q), repeated Q times, q = 1, …, Q of the object 100 to be tested, and calculate the average RI = $\frac{\sum RI(q)}{Q}$ of these infrared responses, and calculate the required significant dimension x of the object 100 by the following relation:

$$x = A_4 \cdot (RI)^4 + A_3 \cdot (RI)^3 + A_2 \cdot (RI)^2 + A_1 \cdot (RI)^1 + A_0$$

Step 5 to transport of the object 100 to be tested to the irradiation support is an automated step that repeats the sequence of sub-operations b) and c) of the calibration step 2 described in detail in the above.

Step 6 to adjust the position of the object 100 with respect to the source 32 and the associated detector 40 is an automated step that repeats sub-operation d) of the calibration step 2 described in detail in the above.

Step 7 to determine the photon intensity I of the photon beam attenuated by passing through the object 100 consists of an activity measurement that is then acquired, processed and interpreted in a manner known in itself.

The acquisition, processing and analysis step 8 of the spectrum obtained is an automated step that uses calculation algorithms known in themselves executed by the dedicated software located on the computer 170 of the acquisition, processing and analysis apparatus 200.

Step 9 to determine the relative variation $\frac{\Delta\rho}{\rho}$ of the density of the object 100 with respect to the density of one or several standard density object(s) emas is shown in summary in Figure 14. This is an automated calculation step in which the $\frac{\Delta\rho}{\rho} = \frac{x_{emas}}{x}\left[1 - \frac{L_{n}\frac{I}{I_{emas}}}{\mu_m \rho_{emas} x_{emas}}\right]$ equation and the data determined in the above steps are used.

The return transport step 10 of the object 100 on its location on the turntable 70 is an automated step that repeats sub-operation e) in the calibration step 2 described in detail above.

The method that has just been described is implemented using a dedicated software. This software comprises five independent modules and a main interactive menu by which an operator chooses to have one of the five modules executed. The five modules include the following functions:

- first module: determine the density of an object that includes the calibration step 3 and steps 4 to 10 to actually determine the density,
- second module: determine the significant dimension of an object,
- third module: calibrate the position of the apparatus to determine the significant dimension,
- fourth module: calibrate the position of the apparatus to determine the attenuated photon intensity,
- fifth module: management of data files.

Example

The system and process described above have been tested.

The source was a ^{133}Ba source with 10 mCi of activity. The duration of acquisitions was of the order of 20 minutes.

Measurements were made on a set of 7 pellets of uranium oxide (UO_2) with the following characteristics: diameter, height and density, as given in table I:

Pellet No.: i	1	2	3 (standard)
Diameter (mm)	8.165	8.143	8.166
Height (mm)	11.54	11.44	11.27
Density ($g.cm^3$)	10.260 ± 0.003	10.130 ± 0.003	9.900 ± 0.003
Standard difference ($g.cm^3$)	1.99×10^{-2}	1.98×10^{-2}	1.96×10^{-2}

Table I

Pellet No.: i	4	5	6	7
Diameter (mm)	8.147	8.123	8.117	8.169
Height (mm)	11.49	11.29	11.54	11.59
Density ($g.cm^3$)	10.150 ± 0.003	9.950 ± 0.003	9.960 ± 0.003	10.070 ± 0.003
Standard difference ($g.cm^3$)	1.98×10^{-2}	1.95×10^{-2}	1.93×10^{-2}	1.97×10^{-2}

Table I (continued)

Pellet 3 is used as a standard pellet.

The purpose of the measurements is the precise determination of the relative variation of the density of pellets (1, 2, 4, 5, 6 and 7) with respect to the density of the standard pellet (pellet 3), using the system and process according to the invention. The following relation is applicable:

$$\frac{\Delta\rho}{\rho} = \frac{x}{x_i}\left[1 - \frac{L_n\left(\frac{I_i}{I}\right)}{\mu_m \rho x}\right] - 1$$

The diameters of pellets assumed to be "unknown" are obtained by the step to determine the significant dimension, in this case the pellet diameter, by infrared radiation.

The results of counts obtained by gamma spectrometry for each of the six pellets are shown in table II. There were obtained scrupulously respecting the method chronology as described above.

PELLET No.	I (in hits)	DIFFERENCES IN DENSITY
1	974725 ± 1974	(3.448633 ± 0.017045) x 10^{-2}
2	1012550 ± 2012	(2.286541 ± 0.061460) x 10^{-2}
4	1009661 ± 2010	(2.344449 ± 0.016572) x 10^{-2}
5	1063886 ± 2063	(6.611105 ± 0.132441) x 10^{-3}
6	1067853 ±2067	(5.941459 ± 0.122442) x 10^{-3}
7	1014895 ± 2015	(1.873675 ± 0.017101) x 10^{-3}

Table II

The standard differences of measured density variations were estimated by an uncertainty propagation calculation. Table III is a table comparing these results with theoretical differences given by the pellet manufacturer.

Pellet No.	1	2	4
$[\Delta\rho/\rho]$theoretical	$3.63636 \times 10^{-2} \pm 2.77 \times 10^{-3}$	$2.32323 \times 10^{-2} \pm 2.78 \times 10^{-3}$	$2.52525 \times 10^{-2} \pm 2.77 \times 10^{-3}$
$[\Delta\rho/\rho]$measured	$3.44863 \times 10^{-2} \pm 1.70 \times 10^{-4}$	$2.28654 \times 10^{-2} \pm 1.65 \times 10^{-4}$	$2.34445 \times 10^{-2} \pm 1.66 \times 10^{-4}$

Table III

Pellet No.	5	6	7
$[\Delta\rho/\rho]$theoretical	$5.0505 \times 10^{-3} \pm 2.797 \times 10^{-3}$	$6.0606 \times 10^{-3} \pm 2.77 \times 10^{-43}$	$1.71717 \times 10^{-2} \pm 2.76 \times 10^{-3}$
$[\Delta\rho/\rho]$measured	$6.611 \times 10^{-3} \pm 1.32 \times 10^{-4}$	$5.9415 \times 10^{-32} \pm 1.22 \times 10^{-4}$	$1.8737 \times 10^{-2} \pm 1.71 \times 10^{-4}$

Table III (continued)

These results are illustrated by the chart in Figure 15. The circles represent the values of $\frac{\Delta\rho}{\rho}$ resulting from the measurement, while the crosses represent the values of $\frac{\Delta\rho}{\rho}$ given by the manufacturer. The interval materialised represents the standard difference calculated from data supplied by the manufacturer.

These results show that the system and the process according to the invention are capable of detecting a relative variation of the density equal to about 6 x 10^{-3} with respect to the pellet chosen as the standard object.